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**The work focused on (1) improving detection limit using terahertz (THz) inspection method for higher sensitivity by developing better sources, detectors, and optical design, (2) testing powder detection for moving objects, (3) detecting effects of wave diffraction on envelope edges, and (4) evaluation of the terahertz wave penetration depth in metals and other materials**

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# Homeland security enforcement using novel terahertz technology · II
# –Final report–

This is the final report for Grant FA5209-06-P-0140. The report is organized as follows:

▪ Part 1: The initial plan of the research project;

▪ Part 2: The results obtained after this one-year term;

▪ Part 3: Publication of the research results;

On behalf of my colleagues I would like to thank AOARD for supporting our research; especially my thanks go to those people who first considered that our activity is worth the grant and who closely supervised our activity to ensure its advance.

## Part 1: Research project

The research plan for this second year was made up of two directions:

A. Improvement of the detection limit for the terahertz (THz) inspection method:

1. Increase detection sensitivity by using better sources, detectors, and optical design.
2. Test powder detection for moving objects.
3. Check effects of wave diffraction on envelope edges.

B. Evaluation of the terahertz wave penetration depth in metals and other materials.

Each section will be discussed in detail below.

## Part 2: Research results

### A. Detection limit

**1) Sensitivity.** By improving the source, detector and the design of the optical system, as well as refining the data processing method, we could lower the detection limit of chemicals to about 1 mg/cm$^2$. The target does not need to be as large as 1 cm x 1 cm, as in previous experiments; the detection can be made on much smaller quantities. Considering that one pixel in the THz images corresponds roughly to less than 1 mm x 1 mm, the smallest quantity of a chemical that can be detected is below 10 μm (as small as a few grains of crystallized sugar).

**2) Movement.** The target movement does not generally influence detectivity, except when the target size is so small that it crosses the terahertz beam for too short a time. This limit time depends on the detection technique; in the usual case an interval of about 10 ms is necessary. This value establishes a correlation between the maximum scanning speed and the minimum target size. For example if the detectable target size is set to 1 cm, the maximum scanning speed is about 1 m/s.

**3) Diffraction.** The envelope edges were expected to produce the diffraction (bending) of the terahertz beam, which could be mistaken for a scattering feature. This effect was indeed found to occur, and the solution found was to detect the envelope edges optically (in the visible or infrared range, or by using data from the associated X-ray scanner) and then remove from the terahertz signal those parts that correspond to edge diffraction peaks.

## B. Terahertz wave penetration

At the specific request of AOARD we introduced in the research plan an evaluation of the possibility of terahertz waves to penetrate certain materials used in container construction, in particular metals, but also concrete and other building materials.

In the case of metals the problem is that they are good electrical conductors, and as such most of the incident terahertz radiation is reflected. A part of the incoming wave does penetrate into the metal volume, but its energy decays exponentially with the depth, at the approximate rate of 1/e (about 37%) for each 0.1 μm. The transmission ratio of just a 1-mm thick plate of metal is then in the order of $10^{-4000}$ (ten to minus four thousand). This is so unimaginably small that in order to get just one photon to pass through, one would need a huge amount of energy: $10^{4000}$ J. To compare, the energy of the whole Universe, assuming that its mass would turn into pure energy, is estimated at $10^{70}$ J.

However, there are cases where metal objects are somewhat transparent in the terahertz range. For example metal plates having a periodic pattern of holes allow in certain conditions the transmission of almost all incoming energy, even though the holes are smaller than the radiation wavelength. Another exception is in the case of porous metals, where the electromagnetic waves are able to find their way through the pores of the material and partially come out from the other side. Unfortunately these findings do not help in the original problem of "seeing" the inside of metal containers.

For heavy construction materials such as concrete and brick, although the reflection and absorption coefficients are not as high as in metals, the THz radiation power available from today's sources and the detector sensitivities prevent "seeing through" walls of regular thickness. Light materials such as wood will probably allow the detection of transmitted THz

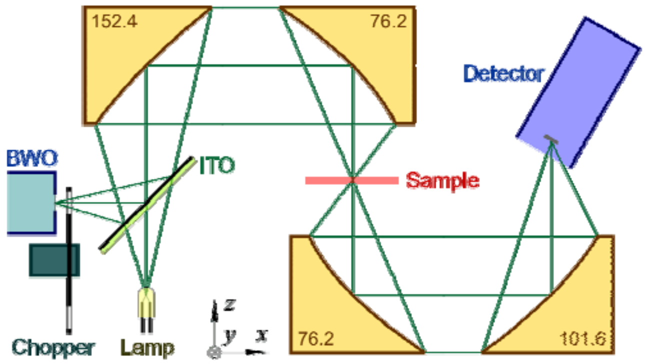


Figure 1. Terahertz imaging setup. The radiation source is a backward-wave oscillator (BWO). The sample is moved *x-y* by a linear-motor stage.


Figure 2. THz image of a Japanese railway payment card. The THz waves penetrate the plastic card and reveal the circuitry inside, including a 6-loop antena for the touch-and-go feature of this card.

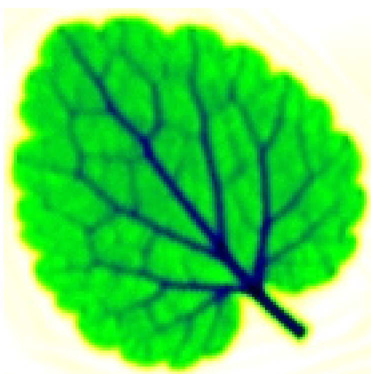

Figure 3. Water distribution in a fresh leaf, by THz imaging.

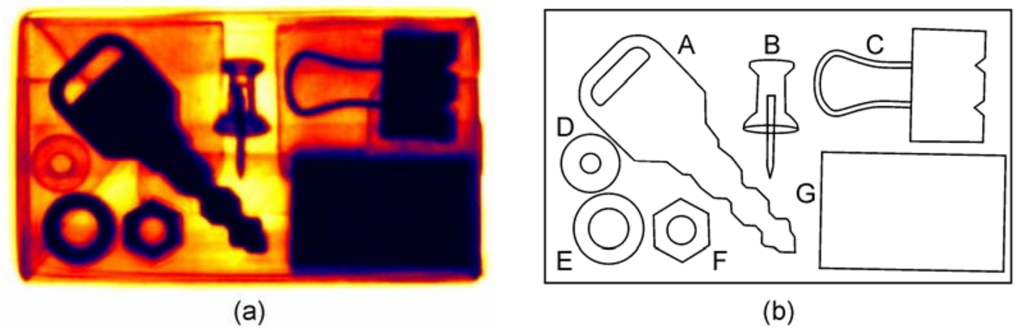


Figure 4. Another example of THz imaging: a closed cardboard box containing several metal and plastic objects. The objects are: A, a key; B, a metal pin with a polystyrene handle; C, a metallic paper clip; D, a polyethylene washer; E, a metal washer; F, a metal nut; G, a 10 mm thick rubber eraser. The box is 80 mm long.

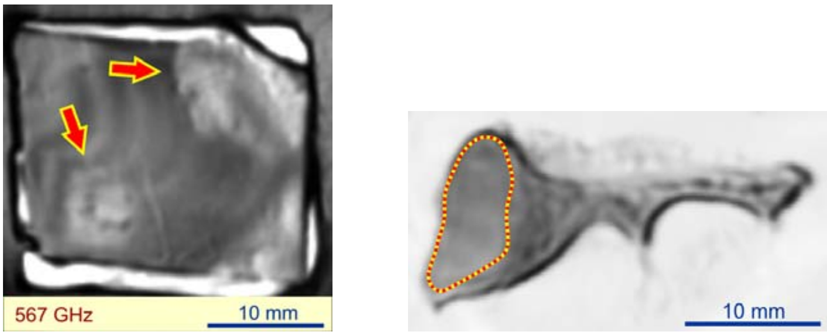


Figure 5. Two medical samples: liver cancer (left) and lung cancer (right). The diseased areas are indicated on each image. However, identification is difficult from these images alone.

waves, but only if the material is sufficiently dry. The absorption coefficient of water is so high that even a few millimeter thick board of wet wood can block too much of the incoming THz waves to allow detection.

## Part 3: Results publication

The results reported here were included in a review article and the presentation in two conferences:

Journal article:

▪ A. Dobroiu, C. Otani, and K. Kawase, "Terahertz-wave sources and imaging applications," *Meas. Sci. Technol.* **17**, pp. R161–R174 (2006) *— see the attached PDF file*

Conferences:

▪ A. Dobroiu, Y. Sasaki, C. Otani, and K. Kawase, "Terahertz-wave imaging in reflection and scattering modes," *2006 Asia-Pacific Microwave Photonics conference*, Kobe, Japan, April 2006

▪ A. Dobroiu, M. Yamashita, Y. Sasaki, and K. Kawase, "Imaging with Terahertz Waves" *ROMOPTO 2006*, Sibiu, Romania, August 2006

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